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Review papers

# Mechanisms and applications of green infrastructure practices for stormwater control: A review

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ABSTRACT

Green Infrastructure (GI) is considered to be an innovative stormwater management approach that offers numerous other environmental benefits including reduction in air pollution and climate change mitigation compared with conventional gray infrastructures, and it has been gradually accepted and used worldwide. This review mainly focuses on the hydrological aspect of GI and provides a summary of the knowledge about GI as a stormwater management alternative. In this review, we discuss the operating mechanisms of a few widely-used GIs in the aspect of stormwater management. We critically examine policies for promoting GI implementation in some countries, including the sponge city in China and water sensitive urban design (WSUD) in Australia, and review the effectiveness of GI on treating stormwater quantity in real world applications. In addition, we also used Bibliometrics to analyze the GI research trends and found GI has been popular in an increasing number of countries and regions, which China has the greatest future growth potential in GIs research. Moreover, many barriers impeding the further development of GI and strategies to overcome these barriers are also summarized. This review gathers knowledge from many sources to provide an overview of GI to better understand its mechanisms and applications, and to highlight the areas that require future study.

## 1. Introduction

Urbanization occurring in the past several decades has considerably changed land use and increased the proportion of impervious surfaces across the world (Berndtsson, 2010; Guan et al., 2015; Yao et al., 2016). Urban hydrological systems have been affected by this increasing imperviousness, as evidenced by increased surface runoff and peak flow, decreased rainwater infiltration and groundwater recharge, and deterioration of water quality (Bell et al., 2016; Chen et al., 2017; Du et al., 2012; Valtanen et al., 2014; Yang et al., 2011). With the combined effects of climate change, the risk of urban flooding may be amplified due to the increasing occurrence of heavy rainfall events and the insufficient capacity of drainage systems (Tao et al., 2014; Wu et al., 2012). Moreover, potential property damage and aquatic ecology deterioration from floods may worsen if this situation persists (Liu et al., 2014c; Zhou et al., 2013). Therefore, several different strategies and technologies have been developed in some countries, such as the low impact development (LID) in the United States, the water sensitive urban design (WSUD) in Australia and the Sponge City in China, which providing a broader framework with a holistic urban water cycle for stormwater management issues (Wong, 2006; Jia et al., 2013; Huang et al., 2015).

Among these strategies, green infrastructure (GI), as an innovate stormwater management approach to mitigate urban hydrology and water quality issues, has been widely applied in many cities around the world (Ahiablame et al., 2012a; Liu et al., 2015a; Wright et al., 2016). Compared with conventional gray infrastructures focused on the reduction of the peak runoff discharge rate by removing water quickly from a site, to reducing flooding using conveyance piping systems, GI practices implement some on-site infrastructures that work with nature to reduce the stormwater runoff and improve water quality from sources using landscape natural features (Ahiablame et al., 2013; Dhakal and Chevalier, 2017; Liu et al., 2014c; Vogel et al., 2015). Thus, GI practices can maintain the site's pre-development hydrological

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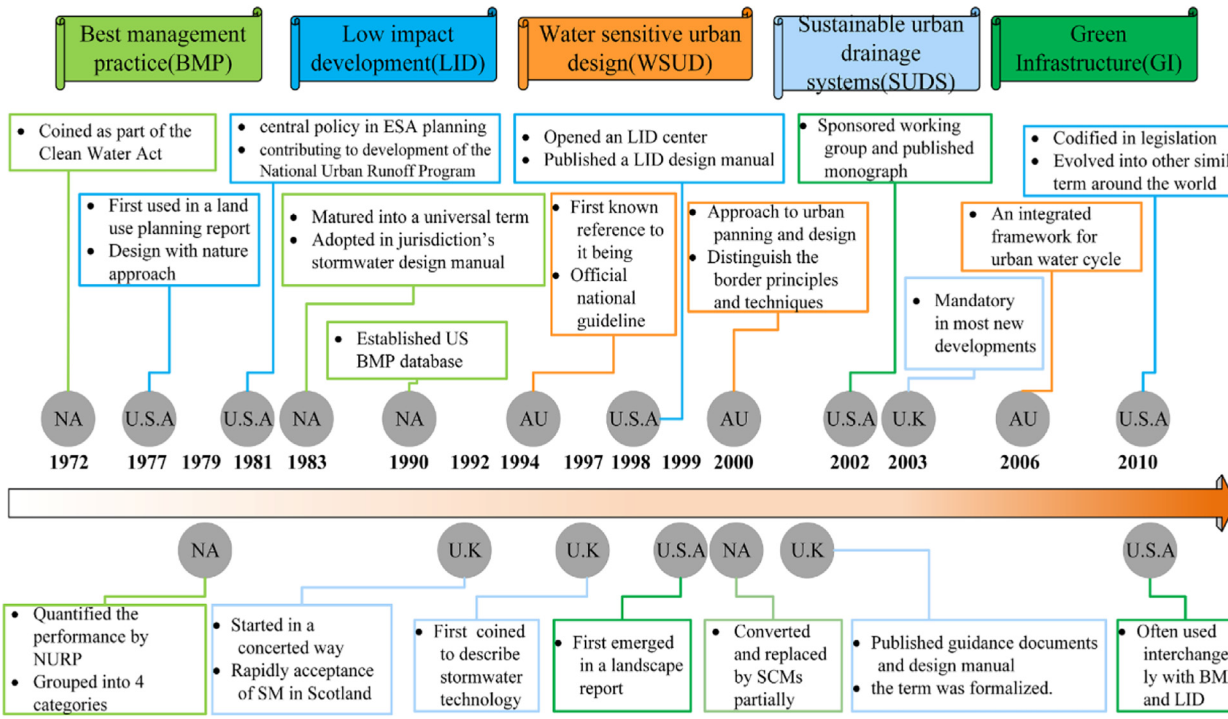


**Fig. 1.** Historical roadmap for development and evolution of stormwater management approaches (BMPs, LID, WSUD, SUDS and GI), the pattern adapted from (Pan et al., 2018). Acronyms: NA (North America); U.S.A (United States of America); U.K (United Kingdom); AU (Australia).

features or reduce the impacts of post-development on urban hydrology (Liu et al., 2014a; Liu et al., 2015b). Therefore, GI practices have environmental advantages for reducing surface runoff and peak flow, enhancing stormwater quality at the source with natural or semi-natural landscapes, thus reducing the occurrence of urban waterlogging and the subsequent damage to urban infrastructure (Ahiablame et al., 2013; Huang et al., 2015; Liu et al., 2014c; Wilson et al., 2015).

Numerous studies have shown the effectiveness and benefits of GI practices in reducing stormwater quantity and enhancing water quality, on laboratory scales, in-situ scales, and modeling evaluations (Autixier et al., 2014; Berndtsson, 2010; Qin et al., 2013; Zhuang et al., 2016). For example, some practices, such as stormwater wetlands and retention ponds, are large-scale practices implemented at the watershed scale to store and control runoff. The other small-scale practices, such as bioretention systems and green roofs, are distributed throughout the site at the source of pollution to treat water quantity and improve water quality (Bell et al., 2016; Davis et al., 2012; Pennino et al., 2016). Even though previous research demonstrated the beneficial uses of GI practices (Wong et al., 2010; Zimmerman et al., 2010), the techniques and widespread implementations of GI practices still need to be greatly improved and promoted, to ensure it is accepted as an effective control stormwater management measure in more countries and cities, and to cope with rapid future climate change. Hence, this paper integrates recent literature, including research articles, peer reviews, technical books, and design and maintenance manuals to support continuing in-depth research and help GI practices attain this goal.

The objectives of this paper are to: (1) describe the fundamental processing mechanisms of several GI practices (specifically rain garden, green roof, and permeable pavement) to deepen understanding and increase use, (2) summarize recent and current research progress related to the effectiveness of the GI practices on stormwater control, and (3) illustrate key barriers to the implementation of green infrastructure from different countries or regions and propose integrated solutions on promoting sustainable storm water management. In general, this review looks to elaborate upon the current development of GI technology, including progress and barriers, from different perspectives, to provide recommendations and strategies for the implementation of GI and to explore and fill the research gaps.

## 2. Overview of green infrastructure

LID was first introduced in Maryland as an alternative land development and ecological engineering design approach to compensate for land development impacts on hydrology and water quality (Fletcher et al., 2015; Vogel et al., 2015). Due to concept similarity, the term LID is also interchangeable with GI practices in urban settings in the United States (Fletcher et al., 2015; Liu et al., 2017b; Mwangi et al., 2015; Struck et al., 2010). Green infrastructure has been defined by multiple studies and reports, so no single, universally accepted definition of GI exists. With reference to the available literature, GI is broadly defined as the interconnected network of natural and semi-natural elements that provide multiple functions and ecosystem services (ESS), including positive ecological, economic, and social benefits for humans and other species (Jacobs et al., 2014; Koc et al., 2017; Naumann, 2011; Sussams et al., 2015). According to the literature review, GI assets were grouped into four high level categories: (1) tree canopy (TC), (2) green open spaces (GOS), (3) green roofs (GR), and (4) vertical greenery systems (VGS) (Koc et al., 2017).

### 2.1. Development of green infrastructure

The concept of green infrastructure originated from the best management practices (BMPs) proposed by the United States in the mid-1980s, to accomplish more holistic stormwater quantity management goals for runoff volume reduction, erosion prevention, and groundwater recharge (Schueler, 1987), and the term formally emerged in 1990s. Alternative terminology includes stormwater source controls, and the LID practices mentioned above. Additionally, many countries around the world have developed and implemented similar approaches using different terminology for stormwater control (Vogel et al., 2015). Sustainable urban drainage systems (SUDS), first initiated in the U.K. and Germany, have been used since the 1990s to mitigate stormwater

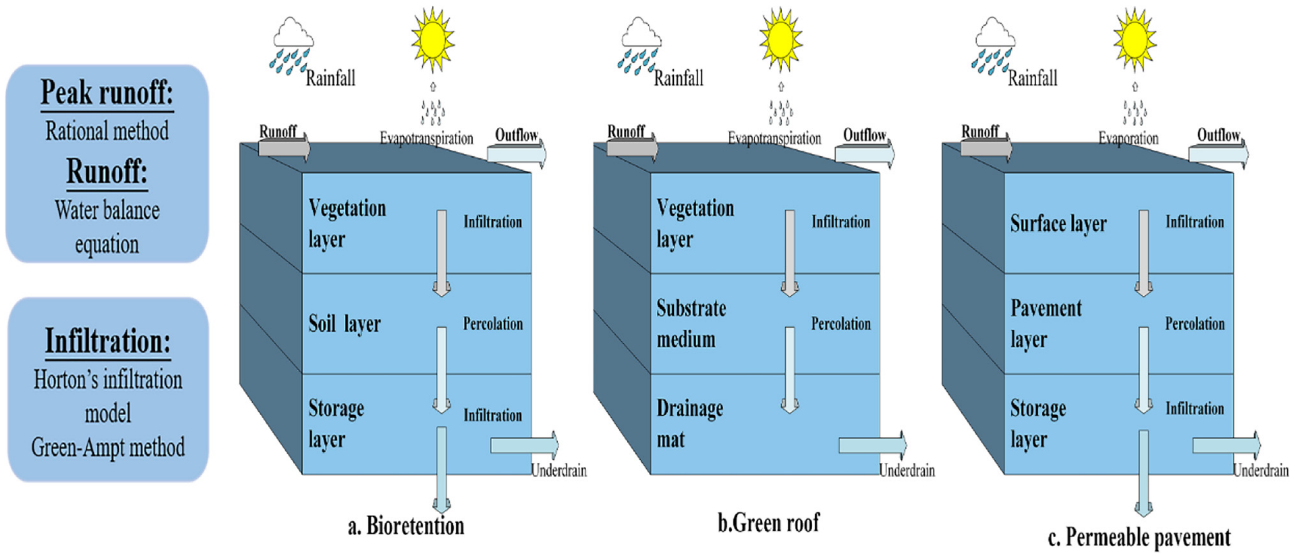


**Fig. 2.** Conceptual hydrological models for three Green Infrastructure practices: (a) bioretention (adapted from Chui et al. (2016)), (b) green roof (redesigned from Stovin et al. (2012)) and (c) permeable pavement (redesigned from Kamali et al. (2017)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

issues (Keeley, 2011). The concept of Water Sensitive Urban Design (WUSD) was first introduced by Australia as early as the 1960′s, but the official national WUSD guidelines were released in the early 1990s (Fletcher et al., 2015). WUSD is being increasingly used internationally, particularly in the U.K. and New Zealand (Ashley et al., 2013). The development and evolution of these interchangeable terminologies are shown in Fig. 1.

### 2.2. Goals of implementing GI practices

The goal of GI practices is to maintain post-development hydrology of a site close to the natural condition present before development occurs (Ahiablame et al., 2012a). Different from conventional stormwater treatment systems, GI approaches manage and control stormwater runoff through the combined use of vegetation, topography, soil, and bioengineered systems, which contribute to the reduction of stormwater quantity (Bowman et al., 2012; Mullaney et al., 2015). Similarly, GI focuses on treating contaminated stormwater runoff prior to entering aquifers, streams, or other receiving water bodies using ecological methods, such as soil filtration, chemical sorption, and biological processes (Hunt et al., 2010). Moreover, with the ubiquitous natural and semi-natural landscape features, GI practices can substantially decrease the urban flooding risks through reducing stormwater runoff and delaying the lag time, thereby reducing the property losses caused by floods.

### 2.3. Significance of implementing GI practices

Numerous research studies and practical applications concluded that GI approaches could effectively mitigate urban hydrology problems (Gregoire and Clausen, 2011; Kong et al., 2017), while providing substantial environmental, social, and economic benefits to communities, companies and citizens (Roseen et al., 2015; Vogel et al., 2015). And cost analyses of the construction and maintenance of LID practices indicate the implementation of these approaches is less expensive than conventional end-of-pipe approaches (Roseen et al., 2015). Therefore, GI can be applied to a wide range of landscape scales instead of or in addition to traditional storm runoff control elements, as well as preserve or restore hydrologic and ecological functions of an urban ecosystem (Liu et al., 2014c). Consequently, the substantial use and widespread adoption of GI practices can reduce the need for expensive gray stormwater drainage systems, as well as the burden of stormwater runoff on urban infrastructure, which can change stormwater management toward a more distributed and at-source approach (Fletcher et al., 2015).

## 3. GI mechanisms for stormwater control

To better manage urban stormwater runoff, better understanding the operation mechanism of green infrastructure is an imperative. In this paper, we selected three widely used green infrastructures: (1) bioretention, (2) green roof, and (3) permeable pavement to introduce its fundamental mechanisms for peak flow control and runoff reduction with a theoretical hydrological model and formula.

### 3.1. Conceptual model

#### 3.1.1. Bioretention

A bioretention system is a landscaped depression designed to receive stormwater runoff from impervious surfaces, composed of several layers of vegetation, filter media, storage, and an optional underdrain (Ahiablame et al., 2012b; Liu et al., 2014a). Within a bioretention cell, stormwater treatment is performed by a range of chemical, biological, and physical processes of plants, microbes, and soils to remove pollutants from urban runoff, and reduce peak flow and runoff volume by Lucke and Nichols (2015) increasing evapotranspiration through vegetation uptake and the lag time via soil infiltration (Brown and Iii, 2011; Lucke et al., 2017; Brown and Iii 2011).

Fig. 2a shows a conceptual bioretention model that is divided into three layers to replicate the hydrological behavior of the system. Stormwater runoff entering the bioretention system infiltrates the vegetation layer, then the infiltrated water percolates through the soil layer until it reaches the storage layer where the stormwater is temporarily stored. The stormwater is finally either discharged downstream through underdrain pipes or infiltrated into the subsoil below the soil bed (Mangangka et al., 2015; Protection, 2016). When the inflow rate exceeds the infiltration rate of the soil column, water starts ponding on the ground surface. When the surface depression depth is exceeded, the excess water becomes overflow and flows out (Mangangka et al., 2015; Zhang et al., 2010). Eventually, most water intercepted by vegetation and retained by depression is converted into vapor and returns into the atmosphere via evapotranspiration (Chui et al., 2016; Mangangka et al.,

2015; Zhang et al., 2010). Therefore, rainfall-runoff processes can be reduced by increasing soil infiltration as well as vegetation evapotranspiration and interception (Davis et al., 2009; Luan et al., 2017).

As a landscaped depression, bioretention mainly reduces stormwater runoff and peak flow rate through surface depression storage, evaporation, and infiltration (Tang et al., 2016). The proportion of water intercepted by vegetation canopy and evaporation is relatively small compared with methods mentioned above, which are not discussed here.

#### 3.1.2. Green roof

Green roofs, also known as vegetative roofs or eco-roofs, are normally constructed with three major layers: a vegetation layer, a lightweight growing medium layer, and a storage or drainage layer placed on top of a waterproof membrane (Carson et al., 2013; Soulis et al., 2017; Yang et al., 2015). Green roofs are commonly divided into two categories: extensive or intensive, according to the thickness of the growing substrate layer. Extensive green roofs are established with thin substrate layers, typically 15 cm thick or less, whereas intensive green roofs are established with deep substrate layers that greater than 15 cm thick (Berndtsson, 2010; Gregoire and Clausen, 2011; Carson et al., 2013). Generally, extensive green roofs are more often applied and studied because of its lightweight, cheap, and maintenance-free properties (Carson et al., 2013; Nektarios et al., 2015). Green roofs can significantly reduce the peak flow of most of the rainfall-runoff and delay the initial time of runoff formation due to their capacity to store water (Karteris et al., 2016).

A conceptual model for water routing through an extensive green roof system was adapted from a hydrological processes of Stovin et al., (2012) to predict the green roof runoff response (Fig. 2b). Firstly, some of the precipitation entering the roof surface is intercepted by vegetation, and the other proportion infiltrates into the substrate medium. Then, the infiltrated water continues to percolate through the drainage mat and leaves the green roof system through the drainage mat and by filtration onto the building top. During this process, if the soil becomes saturated or rainfall intensity exceeds the infiltration rate, the excess stormwater overflows (Yang et al., 2015). The retained precipitation is eventually released back into the atmosphere through evapotranspiration (Soulis et al., 2017). In general, the hydrological processes simulated by the proposed conceptual model can be expressed as follows: the first process intercepts the rainfall with the vegetation layer and the second process allows the rain water to infiltrate the substrate layer which is then stored at the storage/drainage layer (Soulis et al., 2017).

Consequently, the total amount of runoff is reduced by the retaining part of the rainfall that is intercepted by vegetation, and the peak flow rate is reduced by slowly distributing the stormwater that is temporarily stored in the soil layer of the green roof over a long time period (Li et al., 2015).

#### 3.1.3. Permeable pavement system

A permeable pavement system typically consists of a durable and permeable paving surface, a storage bed of open-graded aggregate, and an optional underdrain system (Drake et al., 2013b; Lee et al., 2015). The system is able to facilitate groundwater recharge and decrease surface runoff by capturing water on the pavement surface and then allowing the water to infiltrate the subgrade layer and groundwater (Imran et al., 2013; Kamali et al., 2017).

A schematic diagram of the major hydrologic processes of permeable pavement is depicted in Fig. 2c. As rain falls onto or flows in from upgradient areas, but flows into the surface layer of permeable pavement, the runoff starts to infiltrate into the pavement layer and the next storage layer. As the porous spaces in the permeable layers and storage layer are filled, water percolates into the natural subsoil or discharges downstream through an underdrain pipe (Zhang et al., 2010). Simultaneously, surface runoff occurs if the rainfall intensity exceeds the infiltration rate of the porous pavement, and water captured in the porous space evaporates back into the atmosphere (Lee et al., 2015). The rainfall-runoff reduction processes of a permeable pavement system mainly include infiltration, evaporation, and water storage, which effectively contribute to the reduction of pavement runoff volume and peak flow (Chopra et al., 2010; Imran et al., 2013).

As an infrastructure facility, the permeable pavement processes that mitigate stormwater runoff mainly include infiltration, void spaces storage, and evaporation. In terms of vertical and horizontal exfiltration, detailed information can be found from Lee et al. (2015). This study excludes this part due to its complexity and lack of being widely applied in the analysis.

### 3.2. Hydrological process modeling

To quantify the effectiveness of green infrastructure on runoff volume reduction and peak flow control, the Colorado Urban Hydrograph Procedure (CUHP) method, SWMM model, and Rational Method, used to calculate and simulate hydrological performance including infiltration, depression losses, evaporation, and peak runoff rate, are reviewed in this paper. In terms of the reduction in the amount of stormwater runoff, the interception and transpiration by the vegetation canopy are not considered in this study, owing to their limited contribution in comparison to the total losses of the rainfall-runoff process (Liu et al., 2014c).

#### 3.2.1. Infiltration

The Horton model (Horton, 1941) provides a good balance between simplicity and a reasonable physical description of the infiltration process for use in both SWMM and CUHP, and was selected to calculate the infiltration rate in Eq. (1) (Luan et al., 2017):

$$f = f_o + (f_i - f_o)e^{-at} \tag{1}$$

where $f$ is the infiltration rate at any given time $t$ from the start of rainfall (mm/min), $f_o$ is the final infiltration rate (mm/min), $f_i$ is the initial infiltration rate (mm/min)), $a$ is the decay coefficient (one/minute), and $t$ is time (minutes).

Similarly, the modified Green-Ampt equation (Green and Ampt, 1911; Mein and Larson, 1973) can also be used in SWMM to simulate the infiltration process. The infiltration rate $f$ is calculated as follows:

$$f = K_S + K_S\frac{|\psi_f|(\theta_S - \theta_i)}{F}t > t_p \tag{2a}$$

$$f = P \quad t \leqslant t_p \tag{2b}$$

where $K_s$ is the saturated hydraulic conductivity (mm/min), $\theta_S$ is the saturated moisture content (%), $\theta_i$ is the initial moisture content before infiltration began (%), $\psi_f$ is the matric pressure at the wetting front (mm), $F$ is the cumulative depth of infiltration (mm), $P$ is rainfall rate (mm/min), and $t_p$ is the time when water begins to pond on the surface.

#### 3.2.2. Depression

The rainwater collected and held in small depressions is called depression loss, which is the portion not available for runoff. Depression losses also include water intercepted by trees, bushes, other vegetation, and all other surfaces. Table 1 summarizes typical numerical values of depression losses for several land cover types (UDFCD, 2017).

In addition, the calculation of depression losses can also be expressed by mathematical equations. The empirical equation introduced by Linsley et al. (1949) simulates the depression storage process. The depression storage ($Sd_O$, mm) at the initial time step is calculated as:

$$Sd_{\max} = Sd_{\max}\left(1 - \exp\left(-\frac{PC}{Sd_{\max}}\right)\right) \tag{3}$$

where $Sd_{\max}$ is the depression of the pervious area (mm) and $PC$ is the accumulated residual rainfall (mm), which is the rainfall minus the interception and infiltration. The calculation of depression in the next

**Table 1**
Typical depression losses for various land covers.

| Land cover | Range in Depression (Retention) Losses (in) | Recommendation (in) |
|---|---|---|
| Large paved areas | 0.05–0.15 | 0.1 |
| Roofs-flat | 0.1–0.3 | 0.1 |
| Roofs-sloped | 0.05–0.1 | 0.05 |
| Lawn grass | 0.2–0.5 | 0.35 |
| Wooded areas and open fields | 0.2–0.6 | 0.4 |

time step ($S_d$, mm) is based on mass balance:

where $Sd_t$ is the depression in the previous time step (mm) and $Es$ is the evaporation of the pervious depression (mm).

$$Sd = \begin{cases} PC + Sd_t - E_s & PC + Sd_t - E_s < Sd_{\max} \\ 0 & PC + Sd_t - E_s \geqslant Sd_{\max} \end{cases} \quad (4)$$

$$E_s = \min(Sd_t, E_p) \quad (5)$$

#### 3.2.3. Evaporation

The most known and commonly used formula for the calculation of actual evaporation is the Penman-Monteith formula (Liu et al., 2014c). However, given its unreliable to define specific parameters, the uncomplicated formula proposed by Hargreaves and Samani (1985) that simulates the evaporation process using only air temperature was used in this paper. The equation for calculating potential evaporation ($E_p$, mm/d) is:

$$E_p = 0.0023 \times 0.408\left(\frac{RA_{\max}}{\lambda}\right)(T_{\max} - T_{\min})^{0.5}(T_{av} + 17.8) \quad (6)$$

where $\mathrm{RA}_{\max}$ is the extraterrestrial radiation of the surface related to latitude (MJ/m$^2$/day); λ is the latent heat of vapor (MJ/kg), which is usually 2.45 MJ/kg; $T_{max}$ is the maximum daily temperature (°C); $T_{min}$ is the minimum daily temperature (°C); and $T_{av}$ is the average daily temperature (°C). The constant 0.408 was used to convert radiation to evaporation equivalents in mm (Droogers and Allen, 2002).

#### 3.2.4. Peak flow rate

The Rational Method is a simple empirical procedure acceptable for use in design storm analysis in urban catchments that are not complex and are smaller than 90 acres (Hua et al., 2010). The Rational Method, properly understood and applied, can produce satisfactory results for urban storm drain and small on-site detention design, and its calculation formula is as follows:

$$Q = 2.78CIA \quad (7)$$

where $Q$ is the peak rate of runoff (cfs), $C$ is the runoff coefficient (a non-dimensional coefficient equal to the ratio of runoff volume to rainfall volume), $I$ is the peak five-minute rainfall intensity (mm/hour), and $A$ is the tributary area (ha).

Among them, the runoff coefficient $C$ reflects the integrated effects of catchment imperviousness, infiltration, evaporation, natural retention, and interception, all of which affect the runoff volume (Council, 2011). $C$ is mainly affected by soil type and rainstorm recurrence period, which can be calculated as shown in Table 2.

Where: $i$ is the percentage of imperviousness (expressed as a decimal), $C_A$ = Runoff coefficient for Natural Resources Conservation Service (NRCS) HSG A soils, $C_B$ = Runoff coefficient for NRCS HSG B soils, $C_{C/D}$ = Runoff coefficient for NRCS HSG C and D soils.

## 4. Applications of GI for stormwater control

Green infrastructure has been proven to be provide a valuable tool for stormwater control and flooding mitigation, and has been increasingly applied around the world since the late 1990s (Chini et al., 2017; Koc et al., 2017). In this paper, some GI application case studies on different scales across different countries, from North America to Europe, from neighborhood sites to pilot city scales, or even to the entire country, are shown in Table 3.

### 4.1. Performance evaluation: runoff reduction and flood alleviation

The effectiveness of GI practices can be determined by evaluating hydrological functioning and pollutant removal capabilities. The most commonly used structural GI practices, including bioretention, permeable pavement, green roof, and bioswale, which can promote runoff reduction and urban flooding alleviation, were selected to determine their hydrological benefits using field studies and modeling simulations (Chini et al., 2017; Eckart et al., 2017). This section describes and summarizes the performance of the implementation of these GI practices on flood control and stormwater management by reviewing some published articles, books, and official reports.

The effectiveness of GI practices on flood alleviation has been investigated by comparing a base case with various scenarios. The effectiveness can be measured by several indexes, such as runoff volume reduction, peak flow control, and lag time attenuation (Liu et al., 2014c; Qin et al., 2013). Table 4 summarizes the efficiencies of different GI practices on flooding mitigation indexes under various conditions.

#### 4.1.1. Bioretention

Lucke and Nichols (2015) revealed that the percentage reduction in runoff volume and peak outflow rate varied from 32.7 to 84.3% and 79.5 to 93.6%, respectively, between three 10-year old street-side bioretention basins during a series of simulated two-year interval recurrence rainfall events, located in Caloundra, Australia. They noted that the peak flow reduction and attenuation performance of bioretention systems under higher and naturally-occurring inflow rates may be different from these simulated results. During the monitoring period from October 2013 to November 2014, the three bioretention cells were constructed in low permeability soils in Northeast Ohio reduced runoff volume, calculated as the sum of exfiltration and ET, by 36.0, 42.1, and 59.2%. During events exceeding the designed one-year rainfall intensities, peak flow mitigation varied from 24 to 96%. Generally, as rainfall intensity increased, peak flow mitigation decreased, especially for storms with overflow (Winston et al., 2016).

#### 4.1.2. Green roofs

Using a prototype green roof constructed in Pittsburgh, Pennsylvania, U.S., Bliss et al. (2009) determined that the impact of a

**Table 2**
Runoff coefficient equations based on NRCS soil group and storm return period.

| NRCS Soil Group | Storm return period (years) | | | | | |
|---|---|---|---|---|---|---|
| | 2 | 5 | 10 | 25 | 50 | 100 |
| A | $C_A = 0.84i^{1.302}$ | $C_A = 0.86i^{1.276}$ | $C_A = 0.87i^{1.232}$ | $C_A = 0.84i^{1.124}$ | $C_A = 0.85i + 0.025$ | $C_A = 0.78i + 0.110$ |
| B | $C_B = 0.84i^{1.169}$ | $C_B = 0.86i^{1.088}$ | $C_B = 0.81i + 0.057$ | $C_B = 0.63i + 0.249$ | $C_B = 0.56i + 0.328$ | $C_B = 0.47i + 0.426$ |
| C/D | $C_{C/D} = 0.83i^{1.122}$ | $C_{C/D} = 0.82i + 0.035$ | $C_{C/D} = 0.74i + 0.132$ | $C_{C/D} = 0.56i + 0.319$ | $C_{C/D} = 0.49i + 0.393$ | $C_{C/D} = 0.41i + 0.484$ |

**Table 3**
Applications of green infrastructure practices around the world.

| Continent/Country | | Examples of GI applications | | Reference |
|---|---|---|---|---|
| | | Project | Approaches and techniques | |
| Europe | UK | 2015 Town and Country Planning Order | SuDS used: Wetlands, rain gardens, swales, blue roof | Ellis and Lian (2016) |
| | Germany | the Biotope/Green Area Factor program-Berlin | Green roofs, bioswales, facade greening, pervious paving and plantings | Ahern (2007) |
| | | the Emscher River region -'15 in 15' | Constructed wetland, Buffer strip… | Nickel et al. (2013) |
| North America | USA | Maryland's Green Print program | Green infrastructure assessment: Wetlands, forest, green corridors | Conservation Fund (2004) |
| | | Stormwater management in six cities: Aurora, Chicago, Milwaukee, New York, Philadelphia, Portland, Seattle | Green roofs, tree planting, swales, porous pavement, green streets, rain gardens, infiltration zones | Conservancy (2013) |
| | | Master's project in Manhattan, Kansas | Rain barrels and cisterns , rain gardens and other infiltration methods | Musoke (2012) |
| | Canada | Planning of the Greater Montreal area (GMA) | Street trees, rainwater harvesting, PPS, green roofs, | Dupras et al. (2016) |
| Australasia | Australia | Two Melbourne urban subcatchments: Scotchmans Creek and Gardiners Creek | Rain gardens, constructed wetlands, rainwater collection tanks and sedimentation ponds | Adams and Jayasuriya (2014) |
| | | The Greater Sydney region- Sydney urban centre | Green roofs, green wall, tree cover | Lin et al. (2016) |
| | New Zealand | Long Bay, Glencourt Place, New Lymn Town Centre | Vegetated swales, Rain gardens, Rain tanks, filters | Roon (2011) |
| Asia | China | Sponge city: pilot cities, i.e. Wuhan, Chongqing and others | Green roof, roof gutter and bioretention, bioswale and biotrench, pervious pavement, vegetated filter strip and so on. | Li et al. (2017) |
| | Singapore | ABC waters Programme: certified projects, i.e. NTU and NUS. | Rain garden, rain water harvesting, infiltration trench, bio-retention, swale and green roofs, etc. | Lim and Lu (2016) |

green roof on stormwater runoff was substantially better than the control roof. Monitoring and analysis of this site demonstrated that the peak flow rate reduction ranged from 5 to 71% and runoff volume reduction varied from 5 to 69% compared to the conventional control roof for all storms during the monitoring period. From the experimental data of Stovin et al. (2012) for a U.K. green roof test bed on runoff mitigation over a 29-month period, the performance characteristics of the green roof were recorded as 0.04 to 99.95% for rainfall volume reduction, 19.81 to 99.93% for peak attenuation, and the stormwater was delayed by an average of 87.70 min compared with the conventional system. These figures provided a clear indication that green roofs could play a significant role in providing source controls as part of SUDS treatment (Stovin et al., 2012).

#### 4.1.3. Permeable pavement system

An impervious surface can be converted into porous permeable pavement to decrease runoff. A community located in Haidian district of Beijing was selected as a case study to simulate the effect of GI practices on urban flooding reduction. The simulation results showed that runoff volumes were reduced by 46.2–42.0% and peak flows were reduced by 37.9–35.7% under 1-, 2-, 5-, and 10-year storm events, with 50% of impervious surfaces being converted into porous brick pavement. If the impervious surfaces decreased to 0% under the same storm recurrence intervals, that reduction rate would change to 66.5–59.6% and 54.2–51.0%, respectively (Liu et al., 2014c). Drake et al. (2013a) evaluated the hydrologic performance of three partial-infiltration permeable pavement systems in Vaughan, Ontario, Canada over 22 months. The results showed that the PPS completely captured most rainfall events that were less than seven mm deep. A 43% reduction in outflow volume occurred, and peak flows were reduced by at least 50% throughout the study period. These results support that permeable pavement systems can provide sustainable stormwater management for a wide range of complex areas (Imran et al., 2013; Tota-Maharaj and Scholz, 2010).

#### 4.1.4. Optimal combination

Fry and Maxwell (2015) indicated that distributed GI practices (bioretention cells and rain gardens) have the largest impact on peak flow and runoff volume reduction for smaller storm events, in the range of 25–41% and 15.5–25%, respectively, under different configurations of two-year storms in a neighborhood site, Denver, U.S.A. Another comparative study showed that site outflow volume significantly decreased using a LID process (grassed swales, pretreatment bioretention cell, underground detention chamber and underground infiltration trenches), ranging from an 89% runoff reduction for a 79.5-mm storm event, to a 100% runoff reduction for a small storm, and a significant peak discharge reduction for all storms sampled, with reduction ranging from 98 to 100% (Wilson et al., 2015). Luan et al. (2017) revealed that comprehensive measures (a combination of a concave greenbelt with 50% concave ratio, a permeable pavement, a bio-retention cell and a vegetative swale), compared with individual practices, were more effective at reducing peak discharge and runoff for a one-year rainfall event and the reduction percentages were 55.7% and 57.3%, respectively. Xu et al. (2018) developed a fast and reliable method, Marginal-cost-based greedy strategy (MCGS), for GI/LID layout optimization, and was applied to three case studies in China to verify its broad applicability. Results indicate that the simple MCGS has the prominent advantages on the optimization of cost effectiveness and GI layout planning.

#### 4.1.5. Summary

The performance of GI systems is significantly impacted by the size of the storm event, including event duration and peak flow intensity. The reduction efficiency also depends, to some extent, on the magnitude of rainfall events (Tao et al., 2017). GI practices have somewhat better performance for low intensity and short duration events on

**Table 4**
Summary of effectiveness of GI practices on runoff reduction and peak flow control.

| GI practices reviewed | Study area | Runoff volume reduction (%) | Peak flow Control (%) | Lag time (minute) | Reference |
|---|---|---|---|---|---|
| Bioretention | North Carolina, USA | 63.0–89.0 | 84.0–95.0 | – | Brown and Hunt (2012) |
| | Queensland, Australia | 32.7–84.3 | 79.5–93.6 | * | Lucke and Nichols (2015) |
| | Northeast Ohio, USA | 36.0–59.2 | 29–100 | – | Winston et al. (2016) |
| Green roof | Pennsylvania, USA | 5–69 | 5–71 | – | Bliss et al. (2009) |
| | Sheffield, UK | 0.04–99.95 | 19.81–99.93 | 4.5–231 | Stovin et al. (2012) |
| | Athens, Greece | 1–100 | 26–100 | – | Soulis et al. (2017) |
| Permeable pavement | Carolina, USA | 91.1–100 | 12.5–100 | 28-50[a] | Collins et al. (2008) |
| | Ontario, Canada | 43 | ≥50 | * | Drake et al. (2013a) |
| | Beijing, China | 42.0–46.2 (50%)<br>59.6–66.5 (100%) | 35.7–37.9 (50%)<br>51.0–54.2 (100%) | – | Liu et al. (2014c) |
| BMPs/LID | Colorado, USA | 15.5–25.0 (2-year) | 25.0–41.0 (2-year) | – | Fry and Maxwell (2015) |
| | Carolina, USA | 89.0–100 | 98.0–100 | – | Wilson et al. (2015) |
| | Beijing, China | 57.3 (1-year) | 55.7 (1-year) | – | Luan et al. (2017) |

[a] Mean value.
* Indistinct data.

volume and peak flow reduction compared with high intensity storm events regardless of duration (Tao et al., 2017). For example, bioretention facilities can readily capture the entire inflow volume during small events (Ahiablame et al., 2013). However, the reduction capacity for single GI facilities was limited, especially during bigger storm events. Instead, integrating GI facilities can enhance the reduction effectiveness for different storms. Therefore, the optimal combination of integrated green infrastructures is imperative to minimize the impacts of storm runoffs, and implementation in communities may have considerable contribution to urban flood control (Liu et al., 2014c).

Reduction in runoff logically led to a reduction in flood events. During a simulation study in Illinois, U.S. (Ahiablame and Shakya, 2016), implementation with 50–100% permeable pavement and 100% rain gardens in parking lots were the most effective at reducing flooding in the watershed, with the rate of flooding reduction varying from 45.5 to 54.5% for major floods, 28.8–40.8% for action floods, 36.4% for major floods, and 21.6% for action floods. Thus, these practices identified by numerous studies have shown their significant ecological importance given their ability to quickly infiltrate rainwater, reduce the runoff in the catchment area, and decrease runoff peak flows that may otherwise result in high influent flows to water reclamation plants (WRPs) and affect operations or cause local flooding and combined sewer overflow (Kumar et al., 2016)

### 4.2. Analysis and implication of GI applications around the world

As an emerging and popular stormwater management approach, many published articles and practical applications of GI around the world have been completed. To analyze the global research trends and patterns of GI practices, Bibliometrics, an effective tool used to reveal research trends in different scientific fields (Li et al., 2014), was applied in this study. The relevant data were obtained from Science Citation Index database using Web of Science Core Collection, which is deemed to be the most reliable bibliographic source (Zhuang et al., 2016). Many documents related to GI practice have been published; therefore, all available publications of different GI types were not included in this analysis to review the most commonly used and representative types. To be included in this review, the search and selection criteria were as follows. (1) Five representative GI categories were selected to analyze trends: green roof, bioretention, bioswale, permeable pavement, and rainwater harvesting system. Relative keywords, like "green roof*" were used to search all publications that contained these words in the title, abstract, or keywords. (2) Only articles, proceedings papers, and reviews were chosen to represent the professional publications. (3) The literature belonging to these categories and types were published from 2008 to 2017.

Using the above-mentioned search method, a total of 2763 original and peer reviewed articles between 2008 and 2017 were identified as being GI-related, and were chosen for further analysis. Then, seven countries were chosen from the world to represent different continents with a two-year interval during the selected period to analyze the trends in GI.

Fig. 3a shows the number of papers and research trends of these five GI types. The GI-related research experienced significant global expansion in the study period. Among them, the study of green roofs represented the largest proportion, followed by bioretention and pervious pavement. Fig. 3b presents the articles published by the seven countries at four different stages. From 2008 until 2011, the United States was responsible for the largest contribution in the seven countries, accounting for more than half of the published literature. From 2011 to 2017, research expanded in most continents, and China, the U.K., and Australia have been gradually increasing their research contributions, representing 16% (39), 12% (30), 12% (29) of the research in 2014 and 19% (66), 11% (37), 8% (29) in 2017 respectively. The combined total number of their published articles was almost the same as that of the United States alone.

According to these figures, we concluded that North America (mainly including the United States and Canada) dominated GI research, followed by Western Europe (mainly including the United Kingdom, Germany, and France), Eastern Asia (mainly including China and South Korea), and Oceania (mainly including Australia and New Zealand) demonstrating a distinct geographic bias, which is similar to the previous research results (Koc et al., 2017; Zhuang et al., 2016). Moreover, Fig. 3b reveals that the growth rate in China was the greatest, indicating that China has the greatest future growth potential in GIs research.

Through cross-national comparative analysis, key differences between these regions and the increase in GI research around the world were identified, indicating that the application of GI practices has been gradually increasing. Overall, the implementation of GI planning would be relatively easy and various examples of GI application in different countries provided more detailed information about appropriate approaches and techniques. This information provided positive references for the other countries when applying GI to urban construction and stormwater management.

In addition to the practical application of green infrastructure approaches ranging from large centralized public projects to small scattered applications on private properties (Zaręba, 2014), many new and current software modeling tools have been gradually applied to the modeling of stormwater management and economic aspects of GI, such as SWMM, MUSIC, SUSTAIN and Storm WISE Model. These model tools provide cost-benefit or economic analysis of GI practices for decision-makers to select the most cost-effective solution in stormwater management (Jayasooriya et al., 2014). Metropolitan areas like Portland,

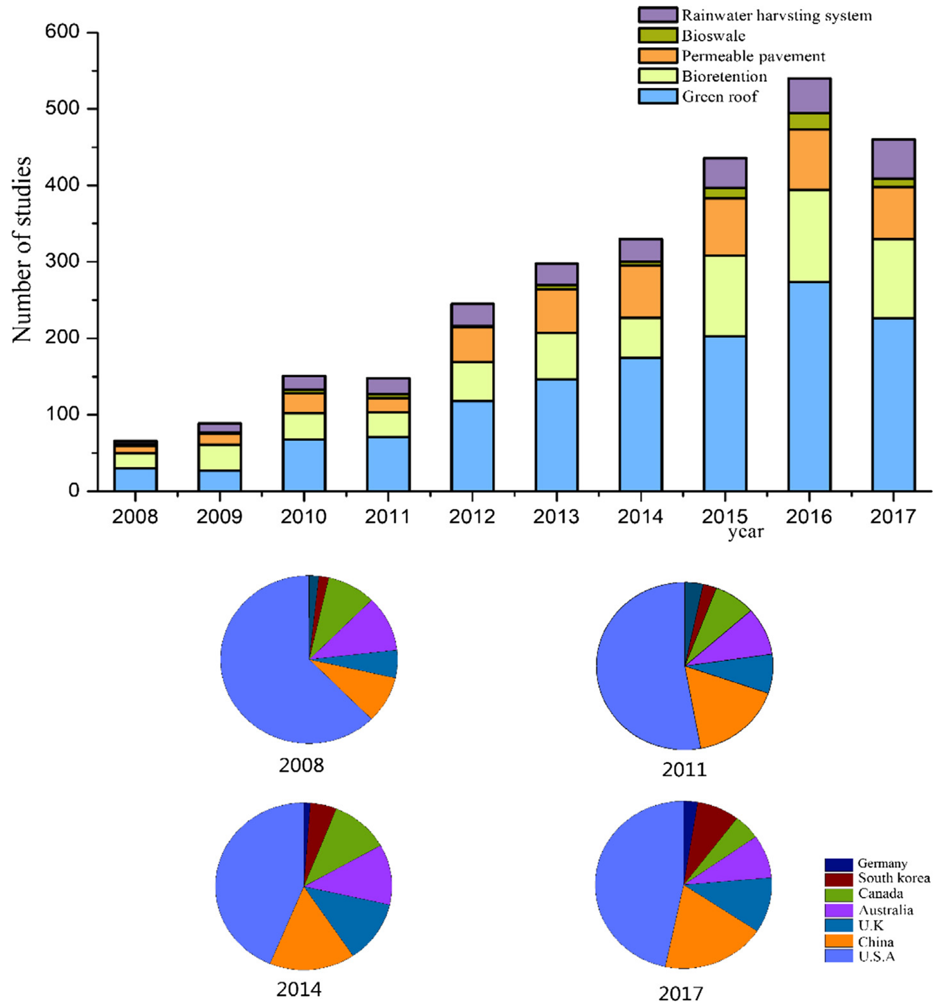


**Fig. 3.** Numbers of research paper of (a) five GI types from 2008 to 2017 and (b) seven countries in different periods.

Oregon, U.S., have already seen the economic benefits of using GI to reduce runoff flowing through their combined sewers. Therefore, the implementation of GI practices can reduce stormwater runoff and result in fewer combined sewer overflow (CSO) events with significant reductions in infrastructure expenditures (Mangangka et al., 2015).

## 5. GI implementation barriers and strategies

### 5.1. Barriers and challenges

Although GI has gained popularity given its environmental benefits and economic advantages compared with traditional gray infrastructure, the process of GI implementation remains slow. Traditional gray infrastructure is still ubiquitous in urban areas throughout the world (Dhakal and Chevalier, 2017). The conflicting relationship between knowledge and practice reveals the barriers that exist to the implementation of GI around the world. According to the literature review, including published papers, government reports and public interviews, both at home and aboard, the main barriers to implementing GI practices can be classified into four categories: institutional, regulatory, technological, and financial. Table 5 presents the recognized barriers for establishing GI practices in four selected countries. The details of each barrier are illustrated in later sections.

#### 5.1.1. Institutional barriers

As shown in Table 5, despite government promotion of the implementation of GI practices and issuance of technical guidelines, implementation remains slow at the local official and community scales due to the inertia of tradition and inflexibility of manuals, as evidenced in China where centralized technical guidance does not apply to local city with different geographical and social conditions (Jia et al., 2017; Xia et al., 2017). Regarding the "inertia of tradition", scholars and researchers argue for institutional change and the strengthening of legitimization processes, but local institutions are still unwilling or resistant to adapt, especially without a successful and secure business case (Brown and Farrelly, 2009). For example, the current price of municipal water in American cities is so low, so residents believe that adopting new water harvesting techniques is not a cost effective method and are thus reluctant to support new GI practices (Labadie, 2011).

#### 5.1.2. Technical barriers

GI is suffering from the lack of sufficient technical support that prevent instant widespread implementation. Based on survey results, most participants agreed that the lack of professional knowledge, such as performance and cost data, design standards and maintenance guidance, and lack of skilled labor were the largest barriers to implementing GI (Kim et al., 2017; O'Donnell et al., 2017). Because if GI practices are not well constructed or applied properly, then they may require special maintenance to perform at a desirable level, or otherwise may result in the unsuccessful operation of GI practices (Bergman, 2013; Edmonton,2016; Shafique, 2018). These technical barriers aroused the uncertainty and skepticism of people toward the use of GI for managing stormwater, and complicating the ability of local governments to allocate funds to GI projects and develop and implement

**Table 5**
Barriers of GI adoption in different countries or regions.

| Barriers | Countries or regions | | | |
|---|---|---|---|---|
| | U.S.A | U.K | South Australia | China |
| Technical/Physical | ● Lack of the knowledge of GI/LID, such as design, construction and maintenance | ● Lack of knowledge, education and awareness<br>● Scientific uncertainty regarding hydrologic performance | ● Lack of information, knowledge or skill<br>● Difficulties in design and construction | ● Unavailable localized technical guidance<br>● Lacking a sound research foundation with ambitious goals |
| Legal/Regulatory | ● No long-term municipal structure for maintenance and ownership<br>● Unclear related duties among agencies and departments | ● Issues with partnership work<br>● Lack of legislation, regulation and governance | ● Regulatory impediments (i.e. planting requirements) | ● Lack of inter-agency cooperation at the local level<br>● Adverse municipal codes and ordinances |
| Community/Institutional | ● Inflexibility of the current manuals and ordinances<br>● Low pricing of municipal water | ● Reluctance to support novel/new approaches<br>● Ineffective/lack of communication | ● Lack of political awareness and interest<br>● Lack of awareness or interest in community | ● Resistance to change<br>● Inertia of traditional approaches at local level |
| Financial | ● Lack of data on cost and benefit analysis<br>● Lack of incentives to encourage implementation | ● Unsecure funding including that for ongoing maintenance<br>● Not enough information about costs | ● Limited access to resources or finance<br>● Lack of incentives | ● Perceived high costs of design, construction and maintenance<br>● Inadequate investment and return estimates |

new stormwater policies (Tian, 2011). For areas that lack technical support, even though they could gain experience from surrounding areas, time and effort are required to adjust measures to local conditions due to specific climates and geography.

### 5.1.3. Financial barriers

Financial constraints are also considered an important barrier hampering the wider adoption of new stormwater management alternatives at the local level. A variety of financial barriers are outlined in Table 5, such as increased overall development costs, limited available investments, a lack of incentives to encourage implementation and cost benefits analysis that show the economic feasibility of GI implementation. Although evidence proved that the use of GI is less costly and more cost-effective compared with conventional approaches, the initial cost of introducing and initiating GI could be high, and periodic labor and cost inputs are needed for maintenance after construction (Tian, 2011). Additionally, many participants stated a lack of local political will for LID/GI has leading to officials being reluctant to support increased fees or taxes, which also involve legal and political issues (Labadie, 2011; Roy et al., 2008).

### 5.1.4. Regulatory barriers

Although GI has been developed and applied since the early 2000s, no mature and specific laws and regulations exist yet to supervise and regulate GI implementation (Li et al., 2017). In many countries, limitations on local and central government rules, regulations, and laws can create significant barriers to the increased adoption of GI. For example, unclear and decentralized responsibilities that lack the close inter-agency cooperation at the local level would postpone GI implementation, especially the shifting of responsibilities between departments that the effective operation management and maintenance of GI infeasible (Jia et al., 2017; Tian, 2011). When GI areas are located on private properties, conflicts between local ordinances and property rights also complicate the completion of long-term and proper maintenance.

## 5.2. Integrated and innovative future solutions

Overcoming the barriers to the implementation of GI can be achieved using various methods. Regardless of barriers being government or individual, academia or enterprise, all can participate in the continued efforts to conquer identified obstacles and facilitate broader adoption of GI practices. In order to develop and improve social, educational, law and economic conditions required by GI practices, a wide perspective and the participation of different stakeholders are needed (Barbosa et al., 2012). Fig. 4 shows the strategies needed to overcome the institutional, regulatory, technical, and financial barriers to the implementation of GI practices. These include: (1) raising public awareness and offering professional education, (2) providing technical support and maintenance guidance, (3) enhancing partnership and cooperation and coordination responsibility, (4) developing financial sources and economic incentives, and (5) modifying policies and establishing regulations and laws.

Firstly, the correct guidance and effective government promotion of GI implementation must be improved. This mainly includes two regulatory and institutional aspects. Specific and appropriate laws and regulations should be introduced by the national government to control stormwater runoff, and should be implemented at all levels of government from top to bottom, to effectively remove barriers in local codes and ordinances. Simultaneously, GI practices would be easier to be implement at the local level, while complying with national requirements. Similarly, integrated collaboration across different levels of government, and interdepartmental coordination with local authority, are critical for identifying the responsibilities across various departments, which are arranged and designated by the government. Thus, a stormwater management committee that plays a significant role in the

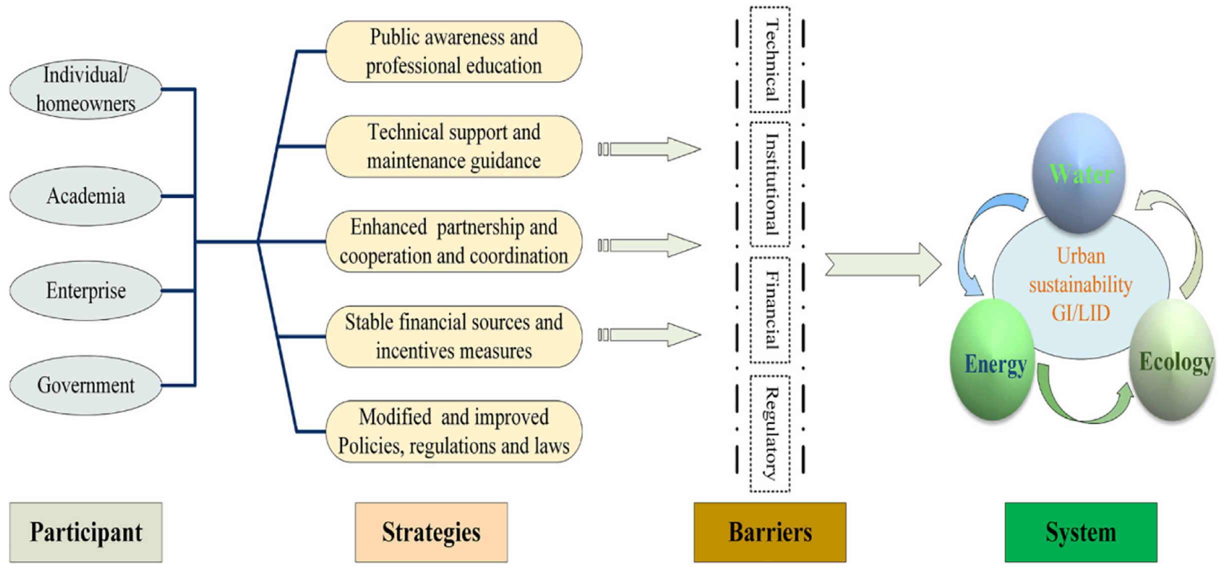


**Fig. 4.** Strategies to overcome barriers to the implementation of GI practices for sustainable stormwater management.

effective collaboration and coordination could be established to promote coordination efforts across levels of government and increase the feasibility of GI construction and development (Hammitt and Geosciences, 2010). For example, an intergovernmental committee was formed to provide guidance on the implementation of Water Sensitive Urban Design (WSUD) practices in Australia (Roy et al., 2008). In addition, sufficient funding resources and economic incentives should be guaranteed and established by the government, to provide financial assistance for long-term GI operation and maintenance, and to motivate local authorities and individuals to adopt GI practices (Frederick et al., 2015).

Secondly, academic and business institutions should undertake the responsibility for knowledge propaganda and technical support to cultivate technical talents, raise public awareness of new sustainable stormwater practices, and create cost-benefit performance database. For example, Professional educators can not only open the stormwater management-GI related curricula and help the government organize public education activities, but can also strengthen scientific research, such as improve the techniques of GI facilities, integrate the GI performance and cost data, and develop design manuals and maintenance guidelines applicable to local climate and soil conditions for engineers and builders. For enterprises, successful design and construction techniques from previous studies and construction experience can be used to reduce construction costs, and provide bonuses for expedited and excellent projects (Tayouga and Gagné, 2016).

Finally, homeowners who have encountered environmental and ecological issues education and have engineering construction training experience can also incorporate GI into their existing landscape, such as rain gardens and rain barrels, which are easily implemented into yards.

In addition to the collaboration and coordination mentioned above, facilitated partnerships between stormwater managers, urban planners, engineers, landscape architects, and urban residents are critical for the increased implementation of GI to stormwater management (Stockwell, 2009).

## 6. Conclusions

Since GI was introduced in the 1990s, it has been increasingly studied and implemented globally (Liu et al., 2017b). Based on its natural design ideas and environmental friendly performances, GI was identified by Sustainable Development as one of the five strategic areas that provide a comprehensive approach to sustainable community development (Walmsley, 2006). Impervious surfaces not only have the largest footprint, but also aggravate rainstorm disasters in urban communities. However, installing green infrastructures would have a profound impact on mitigating urban flooding. This paper presents the operating mechanisms of a few widely used GI in the aspect of stormwater management, including infiltration, evaporation, and precipitation. Policies for promoting GI implementation in some countries around the world were reviewed, including the sponge city in China and water sensitive urban design (WSUD) in Australia. The effectiveness of GI for treating stormwater and urban flooding were summarized, and analysis results revealed that the efficiency of GI varies under different conditions and different regions, and the efficiency of the same GI would change over time. In addition, as the environmental and economic benefits of GI have attracted increasing attention, GI research has grown explosively in the past few decades, with North America takes the leading edge but China has the greatest potential in the field.

Although GI has been gradually applied throughout the world, applying GI on a large scale and achieving the expected goal remains challenging. This paper explored the four barriers to the implementation of GI in different countries: institutional, regulatory, technological, and financial barriers, and the available strategies to overcome these obstacles, including GI design standards adapted to the local ecological environment. For more effective watershed management, continued future research is necessary to improve the GI performance data, especially about the lag time for GI for stormwater. According to the analysis of existing and new data, GI combinations can be optimally selected to achieve the greatest environmental benefit with the lowest expenditure for different conditions and regions (Liu et al., 2014b; Liu et al., 2016a; Liu et al., 2016b). Researchers should also attempt to help decision makers create effective and better GI implementation plans for watershed stormwater management.

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## Additional information

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